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REPORT 417

THE PROBLEMS OF EXACT CALCULATION OF TAKE-OFF AND LANDING CHARACTERISTICS OF CONVENTIONAL TRANSPORT AIRCRAFT

by

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JAN 9 1964

JANUARY 1963

NORTH ATLANTIC TREATY ORGANIZATION

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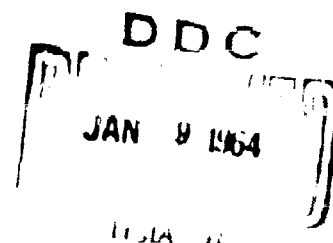
THE PROBLEMS OF EXACT CALCULATION OF TAKE-OFF AND
LANDING CHARACTERISTICS OF CONVENTIONAL TRANSPORT AIRCRAFT

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SUMMARY

The ground roll, transition, and steady-climb phases of conventional take-off calculations often ignore certain factors which are of relatively little importance for small aircraft and long take-off runs, but which may be significantly important for large aircraft and short take-off runs. These factors, and the effect of taking account of them in the take-off and landing calculations, are discussed in this Report.

SOMMAIRE

Les phases du roulement au sol, de transition et de montée des calculs classiques relatifs au décollage négligent souvent certains facteurs relativement peu importants pour les avions de petit tonnage et les distances de décollage longues, mais qui peuvent être extrêmement importants dans le cas des gros aéronefs et des distances de décollage courtes. Ces facteurs, ainsi que les conséquences qui résultent, lorsque l'on en tient compte dans les calculs de décollage et d'atterrissage, sont étudiés dans ce Rapport.

CONTENTS

LIST OF FIGURES

NOTATION

C_L lift coefficient

α angle of attack

$f(v)$ lift function

δ_e elevator angle

v velocity

v_s stalling speed

h altitude

L lift

γ glide angle

w rate of descent

δ_f flap angle

T_R reverse thrust

THE PROBLEMS OF EXACT CALCULATION OF TAKE-OFF AND LANDING CHARACTERISTICS OF CONVENTIONAL TRANSPORT AIRCRAFT

E. Overesch*

1. INTRODUCTION

In conventional take-off calculations the complete manoeuvre is generally subdivided into three different phases. These are ground roll, transition and steady climb. In the calculation of these individual phases it is quite common to ignore factors which do not affect the accuracy of the calculations up to a certain point if they are concerned with small aircraft or aircraft with long take-off runs. However, these simplifications may cause a significant loss in the accuracy of take-off performance calculations for large aircraft which have relatively short or medium take-off runs.

Ignoring the following three factors may have considerable effect:

(1)   Rotation about the Y-axis, which is practically equivalent to ignoring the dynamic longitudinal stability characteristics.

   Generally, take-off calculations are made under the assumption that the lift coefficient C_L or, better, the angle of attack, remains constant within each of the three phases mentioned, and an unsteady increase of lift at the moment of lift-off is assumed.

(2)   The variable forces of the horizontal stabilizer.

   Ignoring these forces, especially under extreme forward centre of gravity conditions, may well have significant effect.

   In general the horizontal stabilizer force which is to be deducted from the total lift is assumed to be either completely negligible or to be constant.

(3)   Ground effect.

   The ground effect exerts its influence in three different ways. On the one hand it causes an increase of lift and a reduction of drag on the wing; on the other hand, due to the decrease of wing downwash in the area of the horizontal stabilizer, a reduction of negative lift on the horizontal stabilizer is caused. It is well known that both effects diminish very rapidly as the aircraft rises from the ground. So the total lift, the drag and the pitching moment become also a function of the flight altitude. The fact that it is not always easy to determine these two functions makes precise computation extremely difficult.

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Usually a simplified method of computing the take-off distance, i.e. the take-off performance, is adequate. In particular, for comparison, it is essential that an exactly predetermined lift function $C_L = f(v)$ be used as the basis of the calculation. This applies also to the landing phase.

2. TAKE-OFF

2.1 Problems Encountered with the C-160

In some instances, however, the take-off characteristics, i.e. the dynamic behaviour of an aircraft during take-off, are of particular interest, in addition to the take-off performance.

With the C-160 we were confronted with the following problem:

The C-160 was to be loaded from the rear by means of a loading ramp.

To facilitate loading it appeared advantageous to move the main landing gear somewhat further to the rear of the aircraft.

We were primarily interested in finding out to what extent the take-off characteristics would change with re-positioning of the landing gear. Would a given change in the position of the landing gear have a marked effect on the dynamic behaviour of the aircraft during take-off?

If the ground roll were accomplished at the same angle of attack at which the aircraft became airborne, the position of the landing gear would have no effect. During the ground roll the C-160 requires an increase in angle of attack of $\Delta \alpha = 6^0$ to become airborne. The extent of the control forces which effect the change in the angle of attack during the ground roll depends on the aft location of the main landing gear relative to the centre of gravity. This is due to the nose-down moment caused by the landing gear forces during the ground roll.

By re-positioning the landing gear further aft the take-off manoeuvre may be influenced in the following two ways:

- (1) If the control forces are insufficient to bring the aircraft into the required take-off position before the selected speed is attained the aircraft will become airborne only at a higher speed, which consequently involves in most cases a longer take-off distance.

- (2) The pilot pulls far enough to enable the aircraft to become airborne at the required speed. If the pilot then does not push quickly enough the aircraft will be exposed to the danger of stalling after becoming airborne.

    I have heard a pilot call this particular reaction of an aircraft the 'sticking effect'. Of course, this expression altogether misses the reasons for this phenomenon, but demonstrates very clearly the effects of this manoeuvre and the feeling of the pilot.

2.2 Composition and Type of the Calculation

To be able to make a precise statement about the take-off manoeuvre it is essential to know all the variables of the motion, especially $\alpha = f(t)$. For an investigation of this nature neglect of the aforementioned factors cannot, of course, be tolerated.

Also, the division of the take-off calculation into ground roll distance, transition and steady climb, which is normally used for simple take-off calculations, is of no help in an exact calculation. Division into degrees of freedom is therefore recommended (Fig. 1).

The marginal conditions must adapt themselves as closely as possible to the natural circumstances. Instead of predetermined values of C_L for ground roll distance and transition, it is, therefore, recommended that a closely defined elevator angle be used. This may be either variable or constant.

The entire subsequent behaviour of the aircraft depends on this angle and the throttle position of the engines which are the only factors directly under the control of the pilot. In this way the calculation very closely approaches a simulation.

It was only with the aid of modern computers that calculations of this type could be successfully accomplished. We used an IBM 650 Digital Computer for this calculation about two years ago.

2.3 Some Examples

Figure 2 illustrates the effect of the position of the main landing gear on the time history of the angle of attack $\alpha = f(t)$. The solid curve represents the angle of attack vs. time with the main landing gear in normal position. For comparative reasons a constant elevator angle is maintained during the complete take-off manoeuvre, the magnitude of which is sufficient to enable the aircraft to become airborne at the right moment, namely at the predetermined value of C_L and the speed associated with this value. The curve of angle of attack in this case is relatively smooth. The increase of the angle of attack with increasing flight altitude must be explained by the decreasing influence of the ground effect on the downwash of the horizontal stabilizer.

The dotted curve shows the time history of the angle of attack for this aircraft with the landing gear re-positioned further aft. The elevator angle again remains constant during the whole take-off manoeuvre, although it is larger by the amount $\Delta \delta_e = 5^\circ$ than the elevator angle of the aircraft with the landing gear in its normal position, in order to enable the aircraft to become airborne at the same take-off speed as the one it is being compared to.

The following conclusions can be drawn:

In the latter case the nose wheel is clearing the ground later, which means a considerable reduction of the interval between the time the nose wheel is clearing the ground and the lift-off of the aircraft. This means that the complete sequence of motions is accomplished in a considerably shorter time.

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After the lift-off an increase of the angle of attack continues for a short time followed by a slight decrease due to the increasing flight path angle. Then, with increasing altitude, the angle of attack increases very rapidly. If the pilot fails to push within this short period of 4 seconds subsequent to unsticking, the aircraft will pitch up as far as the wing stalling condition.

It is quite obvious that an aircraft with the main landing gear re-positioned aft will also take off satisfactorily, provided the pilot reacts quickly enough and decreases the elevator angle. Therefore, piloting techniques for short take-off must be of a higher standard with the landing gear position relatively far aft.

Further studies of various effects on the take-off procedure can be made. Figure 3, for instance, shows to what extent the angle of attack is affected by the position of the centre of gravity.

With an aft centre of gravity position it would be unfavourable to pull too soon as this would cause the nose wheel to clear the ground very early and cause the aircraft to continue the ground roll for some time at a large angle of attack. After the aircraft is airborne the position of the centre of gravity does not influence the angle of attack to any noticeable extent.

Figure 4 illustrates the course of the angle of attack when pulling too early and too much. The interval between the time the nose wheel clears the ground and the time the aircraft becomes airborne is now considerable, and the aircraft continues the ground roll for some time with a large angle of attack. After becoming airborne the pilot must push again early enough, as otherwise, as in the case of the aft positioning of the landing gear, there may be danger of stalling.

2.4 Comparison with Simplified Calculations

A comparison of the take-off performance calculated in accordance with the simplified method with the more exact take-off calculation just described partially disclosed quite a considerable difference in the take-off distances.

The reasons for these differences are easily explained. Figure 5 shows the velocity v, the angle of attack α and the altitude h plotted against the distance covered by the aircraft. The solid curves are the result of an exact computer calculation. The dotted curves show the speed pattern and the highly simplified course of the angle of attack as assumed for the simplified calculation. At first, a difference in the ground roll distances is disclosed. The reason for this difference can be explained by the fact that the negative lift acting on the horizontal stabilizer during the ground roll has not been considered in the simplified calculation. If the ground roll friction coefficient is relatively high, it will be noted that neglecting this factor produces a larger increase of speed during the ground roll.

In the transition phase the difference is much more essential than in ground roll distance. In Method I the transition is found by using a constant value of C_L ($C_L = 0.92\ C_{Lmax}$). In the second case this value is obtained only at the end of transition. The surplus lift ΔL, which is required for the transition phase and which balances the centrifugal force, is effective only after a certain period of time

and not immediately after unsticking. This is accentuated in Case II, in which the C_L-value first decreases after unsticking and later, due to oscillations in the angle of attack, increases only gradually with increasing speed.

The take-off distances calculated by the conventional method are valid only for the most favourable take-off distances which the pilot can approximately meet only by using his utmost skill. Figure 6 shows that an approximation to the optimum course of the angle of attack is possible.

In this case, shortly before the aircraft reaches lift-off speed, the pilot pulls sufficiently to achieve a further increase of the angle of attack after the aircraft is airborne. To avoid stalling, the pilot must push again as soon as a certain altitude has been attained.

Figure 6 shows that the take-off distance calculated by Method II is only 4% in excess of the take-off distance calculated by Method I.

It is an undisputed and generally accepted fact that the distance required for take-off is primarily dependent on the skill of the pilot.

The same applies to the calculation inasmuch as the exact calculation of take-off performance also depends on the pilot, or if expressed in mathematical terms, on the control function $\delta_e = f(t)$. It is this fact particularly which must be clearly stated in the calculation if it is to be reliable and of assistance in specifying the required skill of the pilot during the take-off manoeuvre.

The most important aspect of an exact take-off calculation is not that of the take-off performance, but rather of the take-off characteristics which underline the necessity for a statement regarding the behaviour of the aircraft during the take-off manoeuvre.

3. LANDING

As in the case of take-off, so also in the case of landing, it becomes desirable to be able to carry out an exact calculation for this manoeuvre. In this case the question of interest was to what extent the transition arc can be reduced by the application of reverse thrust during the approach and pull-out. Furthermore, it was again interesting to know how far a manoeuvre of this kind is influenced by the skill of the pilot. For that reason it was important again to study all the variables of motion of the aircraft during the landing phase as a function of time.

For this calculation it was assumed that the reverse thrust does not influence the aerodynamic properties of the wing and empennage. The reverse thrust was to be induced by auxiliary engines suspended on wing pylons.

The landing approach is first made along a steady glide path which is clearly defined by the selected thrust and C_L-value. At a predetermined altitude the pilot

pulls with a specified rate until a given control angle is attained. At a defined distance close above the ground he pulls again gradually until the aircraft touches down. As the position of the throttle will remain unchanged during the approach, the thrust or the reverse thrust, respectively, is merely a function of the flying speed.

Thus the complete dynamic motion during the pull-out is again determined by the control function $\delta_e = f(t)$.

3.1 Description of the Calculation Programme

All curves which are not expressed in terms of exact mathematical functions, such as flight polars, thrust curves, ground effect curves and others, are approximated by polynomials in a preliminary programme. The steady gliding angle γ and the required elevator deflection δ_e are subsequently calculated at a specified approach speed v .

The calculation of the transition can now be commenced. Again, as in the take-off calculations, three degrees of freedom are applied. As the altitude at which the pilot is required to commence the prescribed control manoeuvres to bring the aircraft down at the rate of descent of $w = 0$ is not known, the problem is not one of simple initial values as at take-off but is rather a problem of boundary values. A simple iteration is now carried out. The pull-out manoeuvre is commenced at an estimated altitude. The calculation is discontinued immediately after the rate of descent of $w = 0$ is attained, and the computer will determine the deviation between Δh and the altitude $h = 0$. By deducting this deviation Δh from the initial altitude a new initial altitude is obtained and used to calculate a new pull-out arc. This calculation will be repeated until Δh falls below a specified minimum deviation Δh_{min} . As a rule, this is achieved in most cases at the third attempt.

3.2 Some Examples

The upper part of Figure 7 (Example I) shows a normal landing without the application of reverse thrust. An appropriate control function $\delta_e = f(t)$ has been selected to ensure that the aircraft touches down at the exact moment when it reaches the speed of $v = 1.1\ v_s$.

For reasons of clarity, only the angle of attack α , the altitude h and the rate of descent w are shown as a function of time. The time when the aircraft touches down has, for purposes of comparison, been chosen as $t = 0$.

Flying through the complete transition arc is accomplished in 4.8 seconds. The rate of descent in the initial phase of transition is $w = 6.5$ metres/sec (21 ft/sec). The flight path angle is $\gamma = 8.2^0$.

In Example II (lower part of Figure 7) the pilot pulls at an altitude of 15 metres (50 ft), which is approximately 0.6 second later than in Example I. If the pilot pulls sufficiently a correct landing can still be achieved, although the aircraft now touches down at a speed $v = 1.13\ v_s$ instead of $1.1\ v_s$. The distance flown from an altitude of $h = 15$ m (50 ft) to touch-down is 25 m (80 ft) or 12% shorter than in Example I.

The lower part of Figure 8 shows a landing with reverse thrust used during the approach. If the aircraft is to make the transition at a normal angle of attack, similar to that of Example I and at a touch-down speed of exactly 1.1 v_s, the pilot will have to pull very early, namely at an altitude of 41.5 m (140 ft) and at a flight speed of 1.27 v_s.

At the altitude of 15 m (50 ft) the rate of descent has been reduced to $w = 8.5$ m/sec (28 ft/sec) at a flight path angle of $\gamma = 10^0$. This indicates that the flight path between the obstacle height of 15 m (50 ft) and touch-down is not changed to any considerable extent by the application of reverse thrust. It is mainly the flight path which changes prior to reaching the obstacle height. This does not therefore result in any considerable reduction of transition ($\approx 12\%$). The same reduction of transition can be achieved in Example II by just skilfully applying a somewhat intensified pull.

Figure 9 shows that at the instant the aircraft reaches the obstacle height a significant increase of the flight path angle can only be achieved if an increased pull, namely an increment of the angle of attack, is permitted during the transition phase. Here any shortening of the transition arc is also negligible.

Figure 10 shows an example in which the pilot commences the initial and the second pull too late. In this case the aircraft touches down with a rate of descent of 2 m/sec (6½ ft/sec) instead of $w = 0$. This type of manoeuvre effects a considerable reduction of the transition arc.

Taking all the aspects into consideration, we come to the conclusion that a reduction of the transition arc accomplished with the aid of an increased flight path angle is of little practical value unless the increase in the flight path angle can be associated with a simultaneous increase in lift, which of course is hardly ever the case.

4. CONCLUSIONS

Exact take-off and landing calculations present no problem today which cannot be satisfactorily carried out with the aid of modern electronic computers.

The difficulties in the take-off calculation are for one thing explained by the fact that we cannot count on a uniform cycle of motion; in other words the number as well as the type of equations which represent the motion cycle are changing during the cycle. Another factor contributing to this difficulty is the fact that the individual functions of the aerodynamic forces are influenced by the altitude; this in turn results in more or less intricate functions which cannot always be expressed in a concise mathematical form. The landing calculation is, unlike the take-off calculation, a boundary problem and not one of initial values.

Another question of interest is whether a problem of this nature should preferably be entrusted to a digital computer or whether it would be of advantage to solve it with an analogue computer.

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The analogue computer offers some advantages. For one thing, the calculation is presented in a more distinct way and, furthermore, it provides a continuous check, and corrections can be introduced very simply during the computing process. The procedure is faster and under certain conditions a complete simulation, including that of time, is possible.

The difficulties are due to the very extensive equations involved and also to the fact that some functions are available only in the form of graphs and therefore necessitating several function generators. For this reason either a very large and well equipped analogue computer will be required or the equations will have to be considerably simplified, and this, of course, will always be at the expense of the accuracy of the calculation.

On the other hand, a relatively small digital computer, as for instance the IBM 650, will give very good results.

Ground roll I | Ground roll II | Flight

<u>Degrees of freedom</u>

1 Translation | 1 Translation 1 Rotation | 2 Translation 1 Rotation

<u>Type of equations</u>

Ground roll I:

$$\frac{dv}{dt} = f_1(v, \alpha, \omega, \gamma)$$
$$\frac{ds}{dt} = f_2(v, \gamma)$$

Ground roll II:

$$\frac{dv}{dt} = f_1(v, \alpha, \omega, \gamma)$$
$$\frac{ds}{dt} = f_2(v, \gamma)$$
$$\frac{d\omega}{dt} = f_3(v, \alpha, \omega, \gamma)$$
$$\frac{d\alpha}{dt} = f_4(\omega)$$

Flight:

$$\frac{dv}{dt} = f_1^*(v, \alpha, \omega, \gamma, h)$$
$$\frac{ds}{dt} = f_2^*(v, \gamma)$$
$$\frac{d\omega}{dt} = f_3^*(v, \alpha, \omega, \gamma, h)$$
$$\frac{d\alpha}{dt} = f_4(\omega, \gamma)$$
$$\frac{d\gamma}{dt} = f_5(v, \alpha, \omega, \gamma, h)$$
$$\frac{dh}{dt} = f_6(\omega, \gamma)$$

15 m

Fig.1 Take-off calculation diagram

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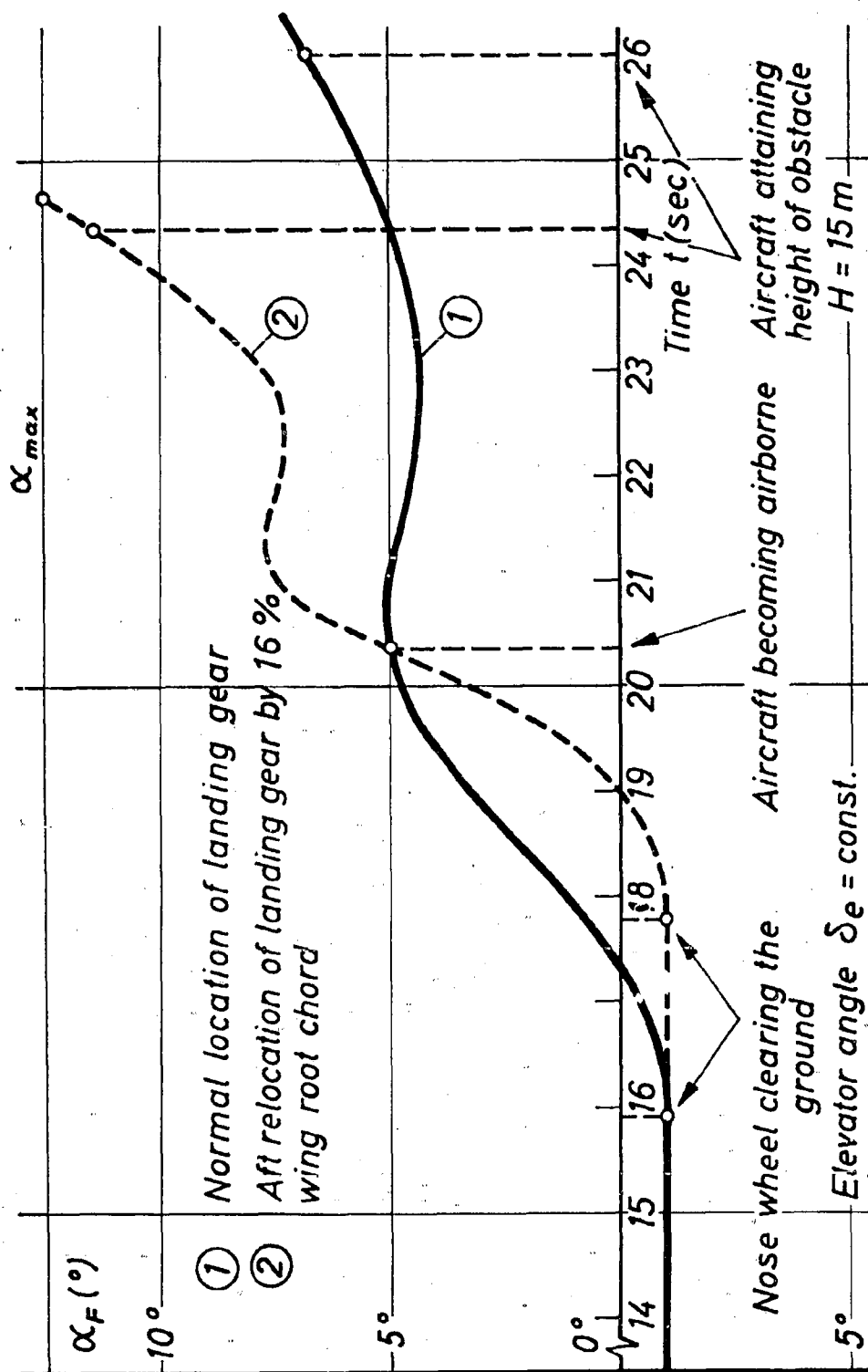
Fig.2   Effect of the main landing gear position on the course of the angle of attack $\alpha = f(t)$

α_F (°)

α_{max}

① Normal location of landing gear

② Aft relocation of landing gear by 16 % wing root chord

Nose wheel clearing the ground

Aircraft becoming airborne

Aircraft attaining height of obstacle

$H = 15\,m$

Elevator angle $\delta_e = const.$

Time t (sec)

Course of the fuselage angle of attack α_F (°)

Speed $v\left(\frac{m}{s}\right)$

Altitude (m)

——— 20 % l_R
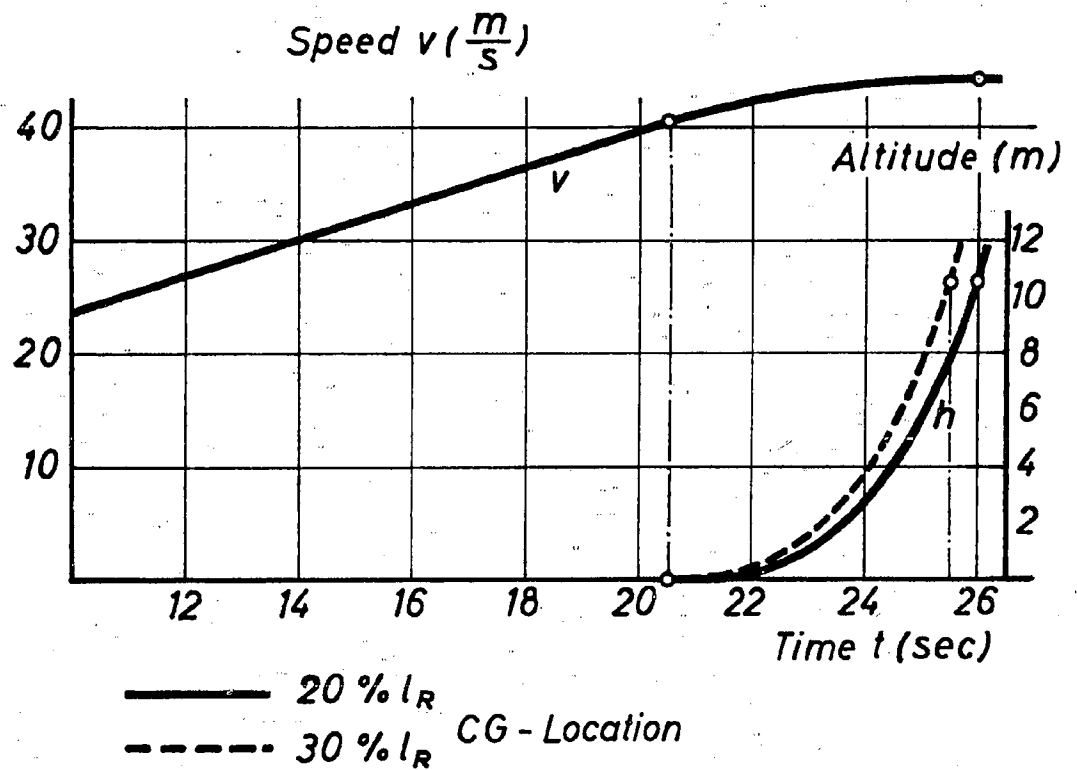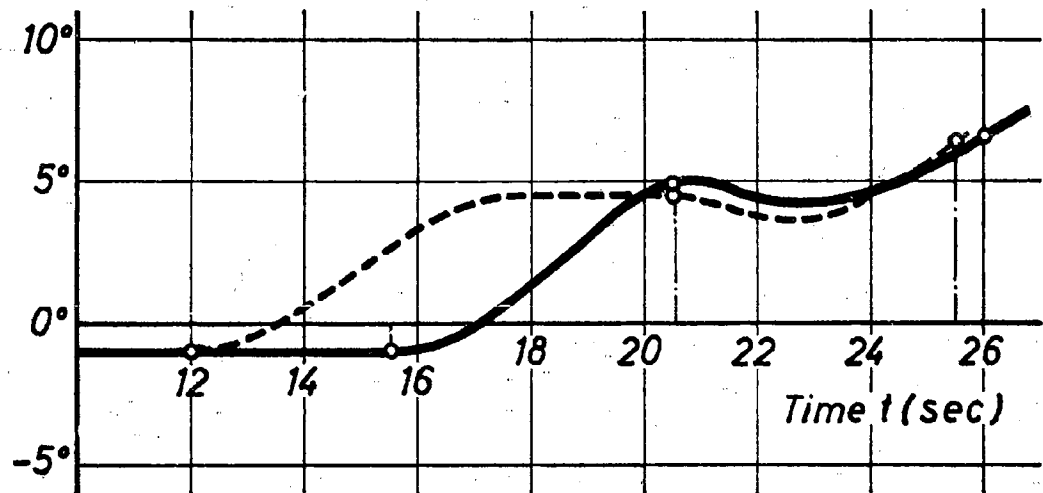
- - - - 30 % l_R CG - Location

Fig. 3   Effect of the position of the centre of gravity on the take-off procedure

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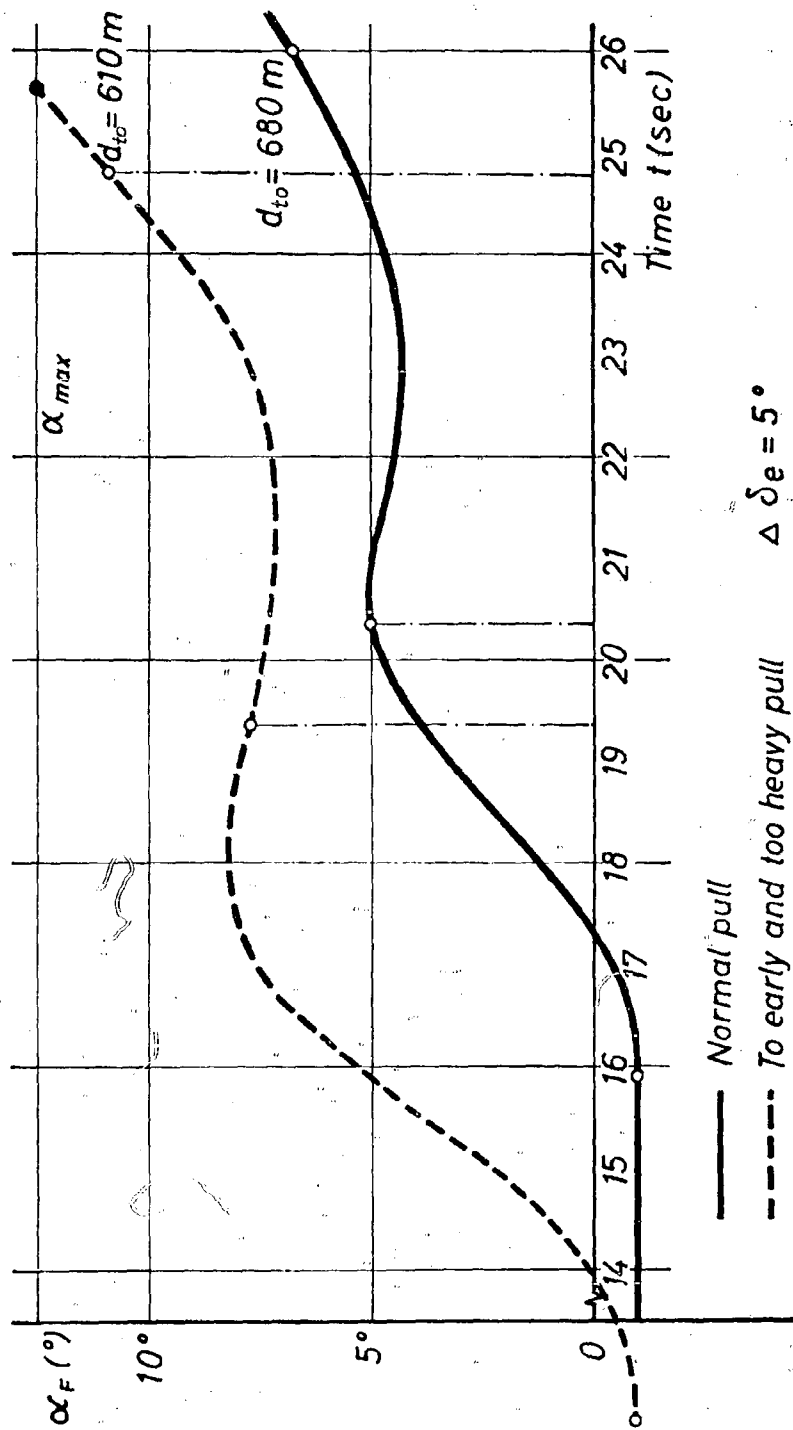
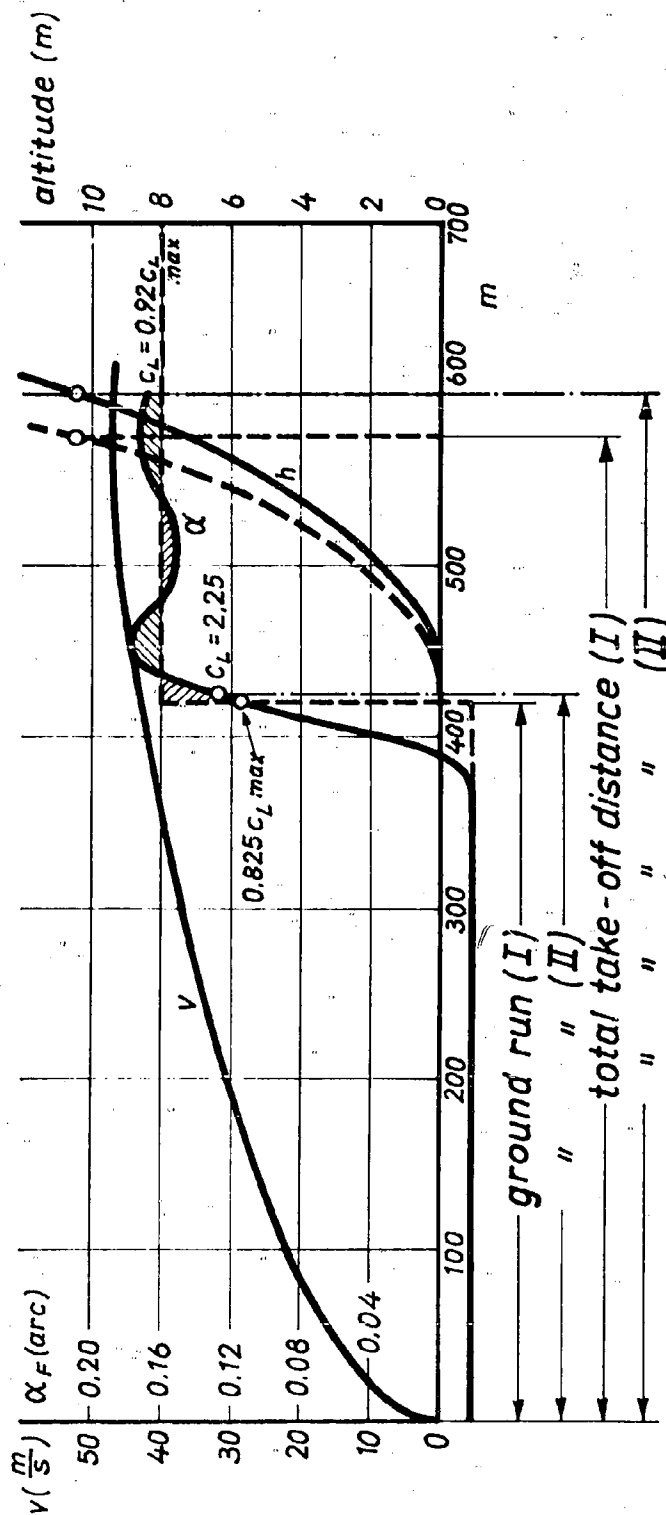Fig. 4 Effect of pull on the angle of attack during take-off

Fig. 5   Comparison of methods of calculation used for the determination of
take-off distances

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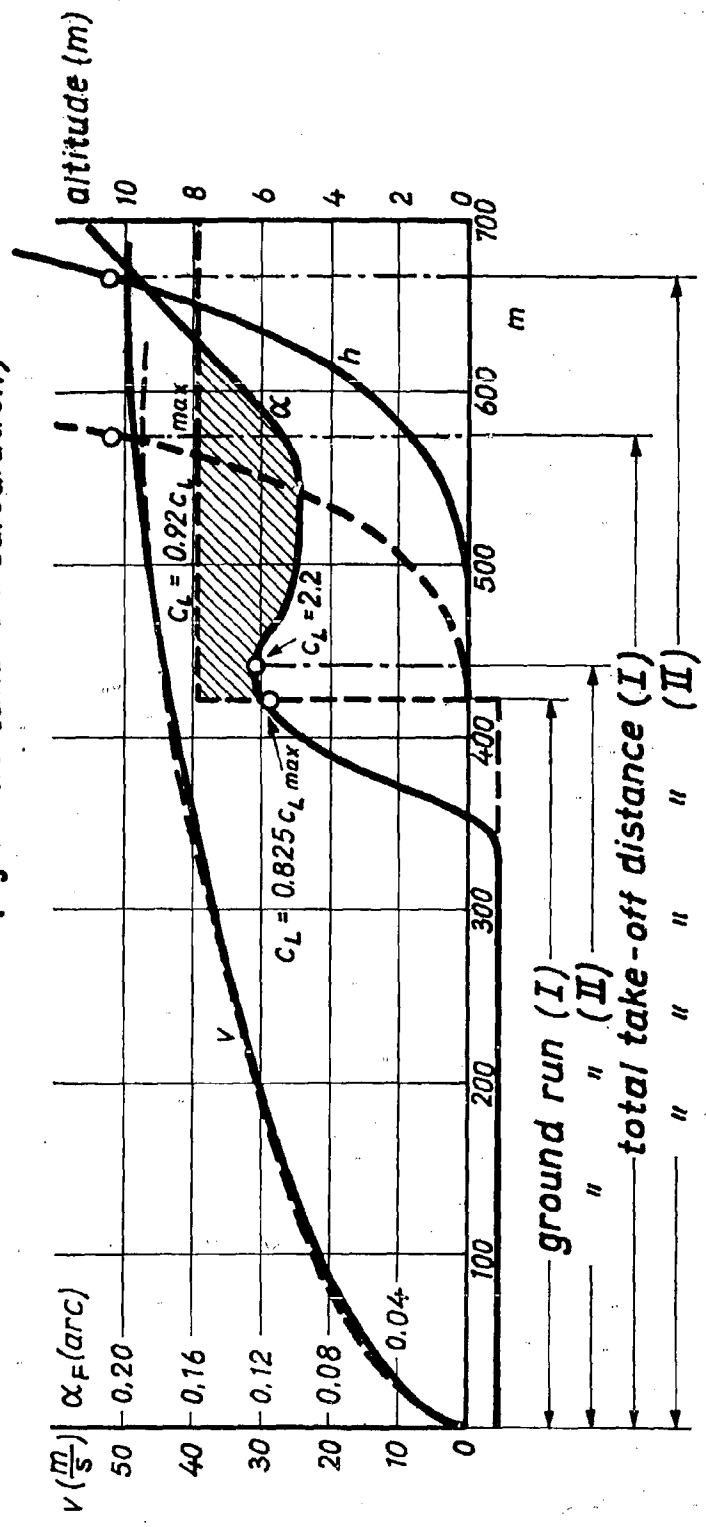
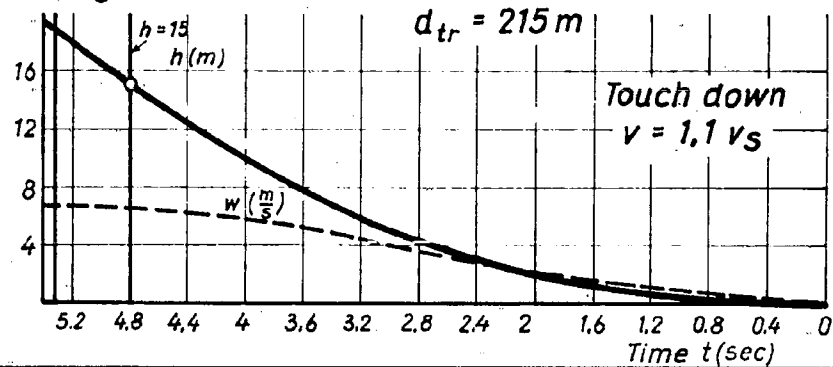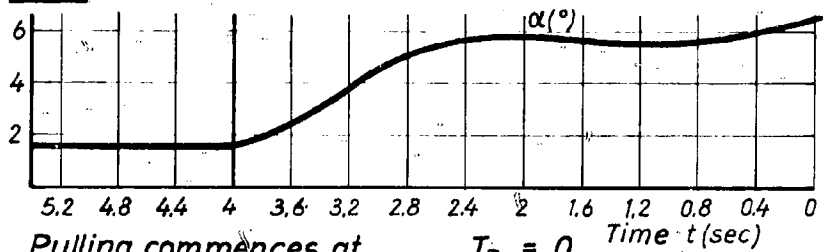Fig. 6 Comparison of methods of calculation used for the determination of take-off distances

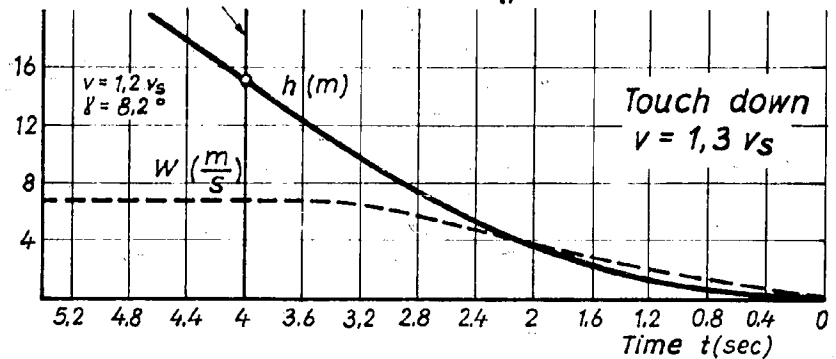## Example I

Pulling commences at the altitude h = 19 m
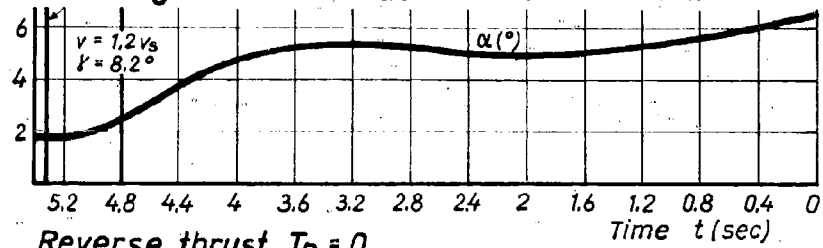
Reverse thrust $T_R = 0$
Length of transition above the altitude of $h = 15\,m$
$d_{tr} = 215\,m$

Example II

Pulling commences at the altitude h = 15 m $T_R = 0$ $d_{tr} = 190\,m$

Fig. 7   Landing computation for the C-160; effect of pulling on the transition arc

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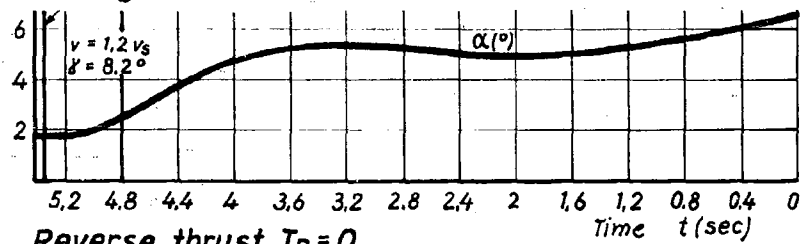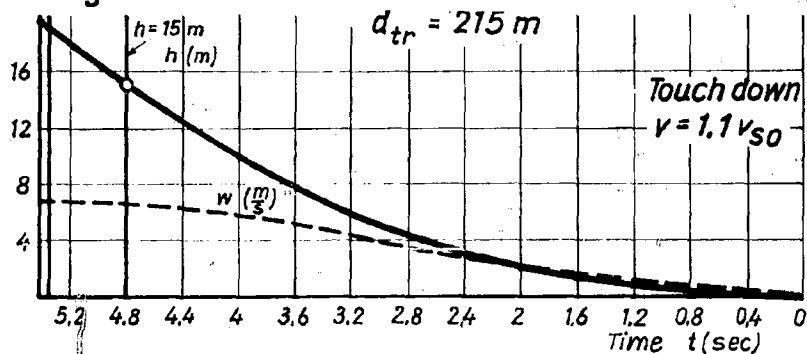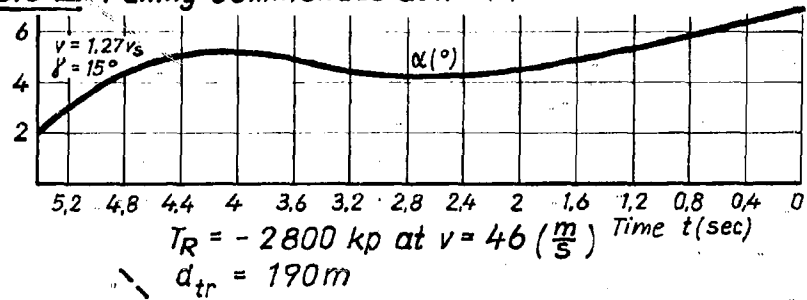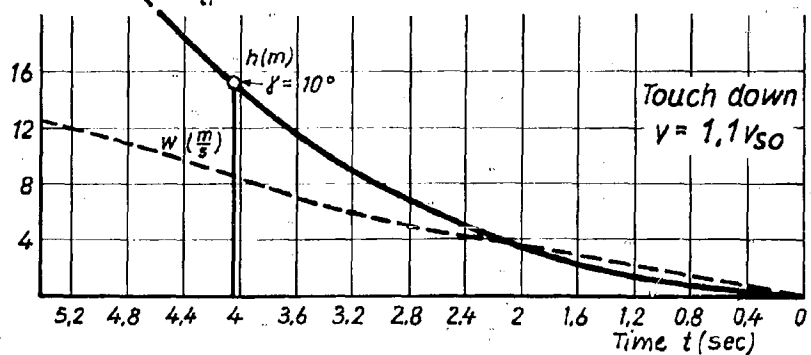## Example I

Pulling commences at the altitude h = 19 m

$v = 1.2 \, v_S$
$\gamma = 8.2°$
$\alpha (°)$

Time t (sec)

Reverse thrust $T_R = 0$
Length of transition arc above the altitude h = 15 m

$$d_{tr} = 215 \, m$$

$h = 15 \, m$
$h \, (m)$

Touch down
$v = 1.1 \, v_{SO}$

$w \left(\frac{m}{s}\right)$

Time t (sec)

Example III Pulling commences at h = 41.5 m

$v = 1.27 \, v_S$
$\gamma = 15°$
$\alpha (°)$

Time t (sec)

$$T_R = -2800 \, kp \text{ at } v = 46 \left(\frac{m}{s}\right)$$
$$d_{tr} = 190 \, m$$

$h(m)$
$\gamma = 10°$

Touch down
$v = 1.1 \, v_{SO}$

$w \left(\frac{m}{s}\right)$

Time t (sec)

Fig. 8   Landing computation for the C-160; effect of reverse thrust on the transition arc

Example III
Pulling commences at h = 41,5 m
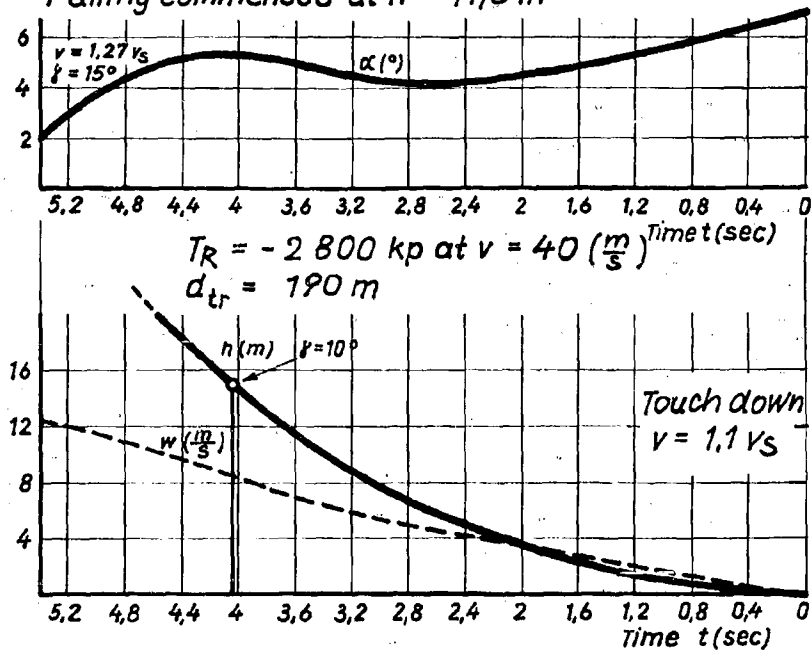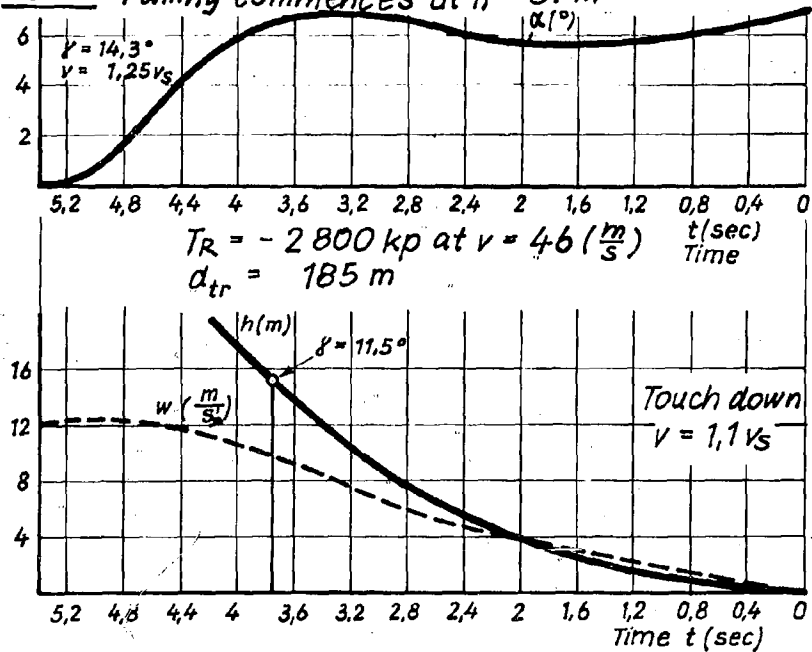
$T_R = -2\,800\ kp\ at\ v = 40\left(\frac{m}{s}\right)$

$d_{tr} = 190\ m$

Touch down $v = 1,1\ v_S$

Example IV Pulling commences at h = 39 m

$T_R = -2\,800\ kp\ at\ v = 46\left(\frac{m}{s}\right)$

$d_{tr} = 185\ m$

Touch down $v = 1,1\ v_S$

Fig. 9 Landing computation for the C-160; effect of pull on the transition arc with reverse thrust

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Example IV
Pulling commences at h = 39 m

$$T_R = -2800 \text{ kp at } v = 46 \left(\frac{m}{s}\right) \quad \text{Time } t \text{ (sec)}$$
$$d_{tr} = 185 \text{ m}$$
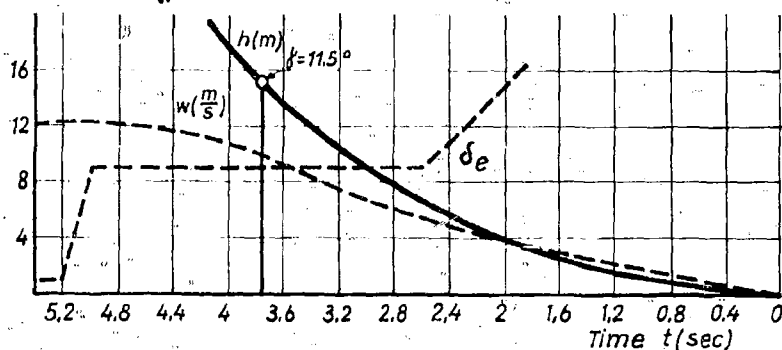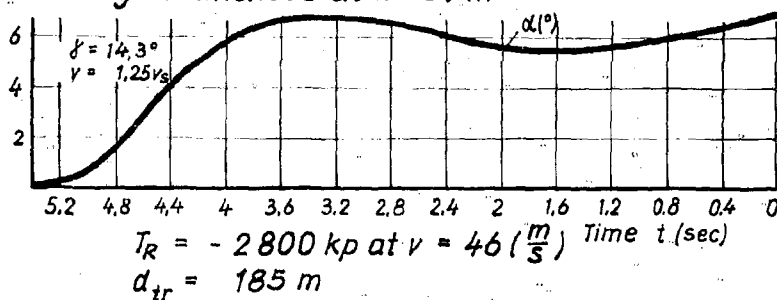
Example V — Pulling commences at h = 34 m

$$T_R = -2800 \text{ kp at } v = 46 \left(\frac{m}{s}\right) \quad \text{Time } t \text{ (sec)}$$
$$d_{tr} = 150 \text{ m}$$
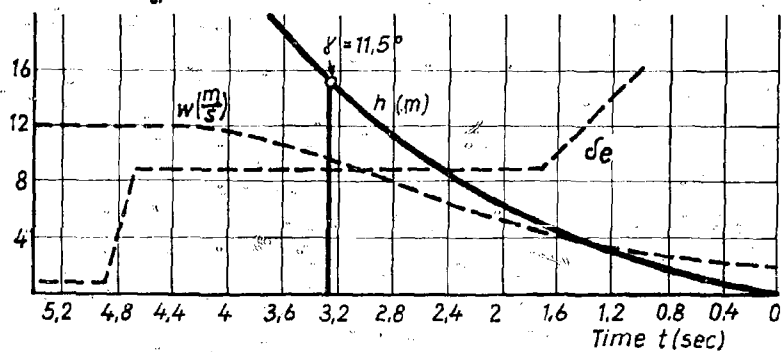
Fig. 10   Landing computation for the C-160; effect of pull on the transition arc with reverse thrust

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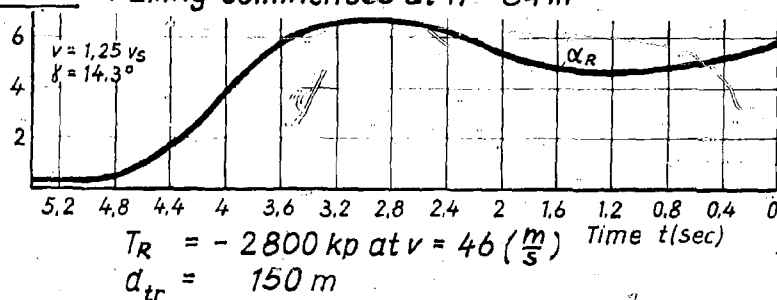Copies of AGARD publications may be obtained in the
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